TRANSIENT RESPONSE CHARACTERISTICS OF PHOTO TRANSISTORS

by George T. Daughters II

I. INTRODUCTION

This paper reports the measured transient response characteristics of three Fairchild silicon planar photodevices (types 1N3734, 2N986, and 2N2452), and presents a circuit model of the transistor which is valid for steady-state, small-signal and large-signal cases. The phototransistor is characterized as a common collector transistor amplifier driven by a fast rising current source which represents the collector-base diode photocurrent produced when the base, collector-base transistion layer, and collector area near the junction are illuminated.

It is well known that a p-n junction diode is photosensitive. Furthermore, the photocurrent flowing when the diode is reverse-biased and illuminated is directly proportional to the incident photon density. This relation can be expressed mathematically [1]

$$I = \eta F_o q A \qquad (1)$$

where I is the photocurrent (the difference between total current when the diode is illuminated and the dark leakage current), η is the quantum efficiency (the ratio of the carriers taking part in a current flow and the number of incident photons), F_o is the fraction of incident photons transmitted (not reflected at the surface), q is the electronic charge, and A is the active area of the device.

The quantum efficiency is independent of the applied voltage, temperature and incident flux.* Thus it is clear that the photocurrent mechanism is quite accurately described by a current generator which has a very small shunt conductance.

The transient characteristics of the photodiode show that this current generator can be turned on and off in less than fifty nanoseconds for all of the diodes studied. Since this is much faster than the faster of the two types of phototransistors studied, the time constants of the photodiode are neglected in the following discussion. [1]

Normal transistor action occurs in the phototransistor, with one exception. The majority-carrier control charge in the base is equalled by a minority-carrier charge (both photoelectrically produced) which moves across the collector junction and adds to the emitter-injected collector current. The resulting steady-state photocurrent is given by (see Appendix)

$$I_\ell = (h_{FE} + 1)\eta q F_o A \qquad (2)$$

*The quantum efficiency actually increases as the depletion layer thickens with larger reverse bias; it also increases at higher voltages due to carrier multiplication effects. The change in diffusion constant of carriers and energy gap of the material with temperature also affect the quantum efficiency. The effects are negligible under normal conditions.

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When the phototransistor is illuminated by rapidly chopped (square-wave modulated) light, it is found that the photocurrent exhibits a marked time dependence. In considering the action of the phototransistor, it is important to note that the input signal is the base-collector majority-carrier photocurrent. This fact suggests that a common-collector representation of the transistor amplifier would describe the phototransistor's behavior in terms of a familiar model. This configuration of the transistor is seen to be a good choice for the steady-state as well as for large-signal and small-signal a-c conditions. Since the source (collector-base photodiode) impedance is so high, the input signal is represented by a current generator.

II. EXPERIMENTAL TECHNIQUES

The experimental part of the study was in two main phases. The first was a set of data characterizing the d-c (steady-state) behavior of several typical photoresponsive junction devices. These were all silicon devices, and included Fairchild types 1N3734, 2N986, and 2N2452. Measurements made included V-I characteristics at various light levels, β at various currents, output conductances, capacitances, etc. These measurements are straightforward and quite simple.

The second phase of measurement was aimed at determining the transient response of these photodevices, from which their gain-bandwidth products would be calculable.

The high speed light source was a GaAs diode utilizing its forward-biased injection luminescence. The spectral peak of the diode's light output is at about 0.9 μ. This is quite close to the peak response of the silicon devices. The diode was driven by a pulse generator capable of two amperes output into this diode at approximately a 1-Kc repetition rate. The rise time of the generator was less than thirty nanoseconds, but the rise time of the light output of the GaAs diode was dependent upon current through the device. The input to the GaAs diode used in this study was kept at a value which gave rise times of at least five times as fast as the devices under test (<100 nsec). With these fast rise times, a valid assumption is that the input drive current into the phototransistor is a step function.

III. SUMMARY OF EXPERIMENTAL RESULTS

Photodiode

The photodiode's characteristics, shown in Fig. 1, justify its representation as a current generator which has an output directly proportional to the number of incident photons, and independent of voltage and temperature. This current source is capable of responding in a time of less than 100 nsec, the bulk minority-carrier lifetime for the particular devices studied. In addition to this time dependence, the current source is shunted by a capacitance, the collector-base transition capacitance (highly voltage dependent),* and a series spreading resistance calculated to be 5 ohms or less is present. Obviously, with low values of load resistance (less than 1 KΩ), the photodiode is carrier-transit limited and not RC time-constant limited. (This can be shown by calculation.)

An equivalent circuit of the photodiode which has the required characteristics is shown in Fig. 1. The dark current conductance has been neglected since it is usually 10^{-10} to 10^{-12} mho.

Phototransistor

Considering the phototransistor as a common-collector transistor amplifier driven by a very high-impedance current source, we find close agreement with experimental results. The characteristics of Fairchild Semiconductor phototransistors are shown in Fig. 2.

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* The relationship of C and V for large and small reverse bias is given by C. T. Sah (Ref. 2).

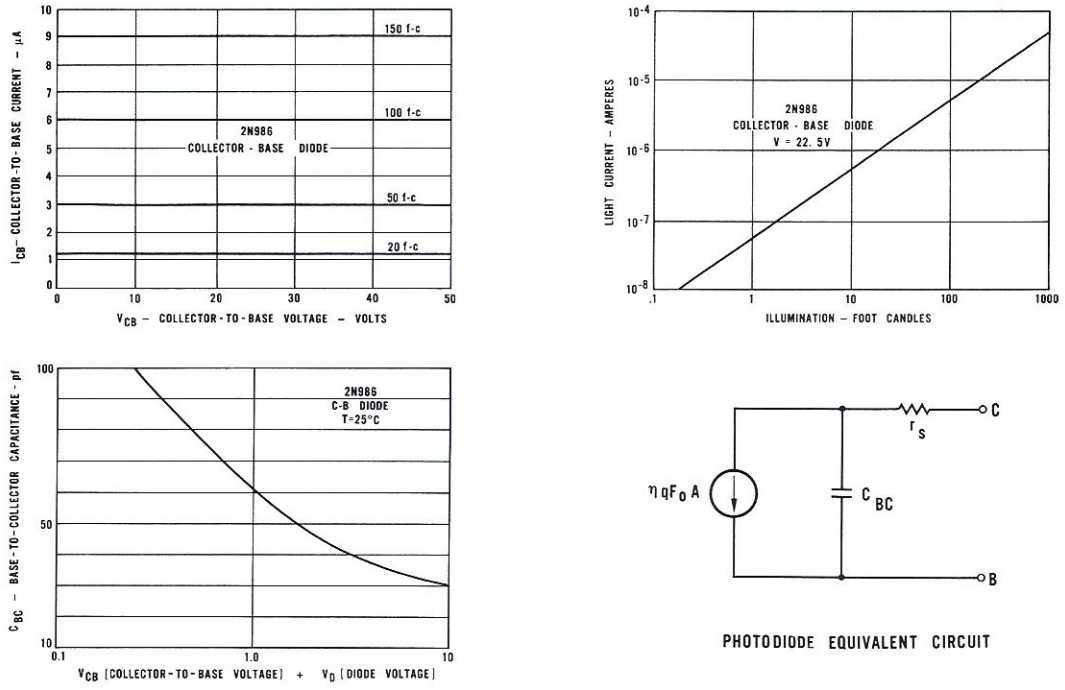

FIG. 1. Photodiode characteristics and equivalent circuit.

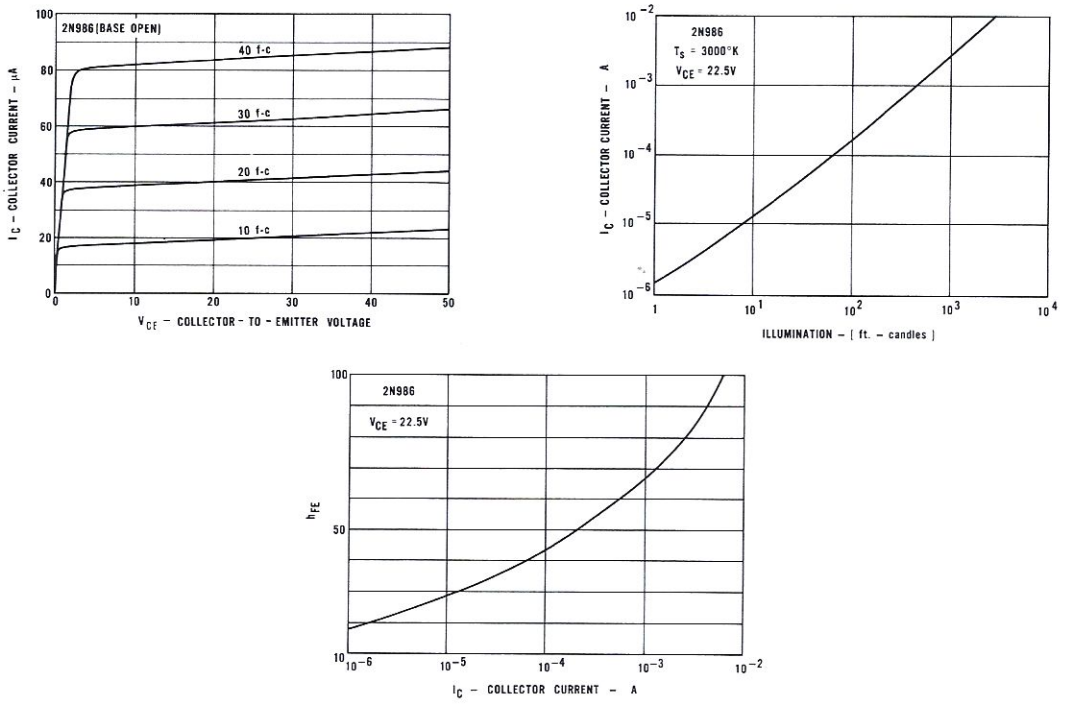

FIG. 2. Phototransistor characteristics.

The small-signal response of the phototransistor can be summarized in qualitative terms with a few simple statements. The rise time of the small-signal output voltage across $(\beta + 1)R_L$ in Fig. 3 equals the fall time, and their wave shapes are very nearly exponential. The time constant of the rise and fall is highly dependent on current. At low values of quiescent current (for example 10 μA) the time constant of an experimental device was 6 μsec. With the same signal, but a quiescent current of 1 mA, the time constant was a full order of magnitude lower. All of the phototransistors studied exhibited this behavior; i.e., decreasing time constant with increasing current, and a limiting value (a minimum) reached when the d-c current is above 1 mA.

From Fig. 3 it is evident why this time constant is a decreasing function of current. At the low levels normally encountered in phototransistor applications, the β of the transistor increases rather slowly as the current increases (see Fig. 2), but the value of r_e varies inversely with the first power of I_e.* This gives a net decreasing resistance (assuming the load resistance is less than r_e), through which the base capacitances charge and discharge.

With small-signal excursions from any given quiescent current, the β and r_e of the device are essentially constant, so the resulting charging and discharging processes are exponential.

The method of obtaining the quiescent current is very important. Two successful techniques have been tried. The first technique was the addition of an external resistor between the base and collector. If care is taken to keep the capacitance associated with this addition very low, the response of the phototransistor can be enhanced considerably. ** The second technique used to apply d-c bias to the transistor was a steady d-c light. This technique is also simple and effective since it adds no additional capacitance to the circuit. All that is required is a flashlight bulb, a battery, and a rheostat to control the bulb brightness. When this light falls on the phototransistor, quiescent currents up to a milliampere are easily obtained. When the phototransistor is subjected to a large amplitude-pulsed light signal, the resulting waveform is very complicated (see Fig. 4) because of the simultaneous changing of many of the transistor parameters.

When the transistor is biased to a high quiescent current, the gain can be quite high, and the 10% to 90% rise time of the output signal can be made quite small (even with large input signals), on the order of a microsecond for the devices studied. This technique, of course, has the disadvantage of high power consumption, even in the no-signal condition. Also, the noise is again higher than in a no-bias condition, but with large-signal amplitudes this is probably of little importance.

With the transistor unbiased, the standby (no-signal) power consumption is very small (the dark currents of silicon planar devices being on the order of 10^{-9} amperes). The rise times are more than adequate for applications such as high-speed photoelectric reading of punched cards and tapes, etc. As a rule of thumb for applications of the phototransistor as a switch, "light equals speed" should be used.

IV. CONCLUSION

The photodiode has been found to be a very fast current generator, and the phototransistor can be accurately characterized as a common-collector transistor driven by the (collector-base photodiode) current generator.

*The value of r_e is given by mkT/q where m is between 1 and 2 (Ref. 3).

**If any external impedance is added between the base and emitter, however, a resulting decrease in gain occurs, coupled with an increase in speed. This is obvious when the equivalent circuit in Fig. 3 is considered.

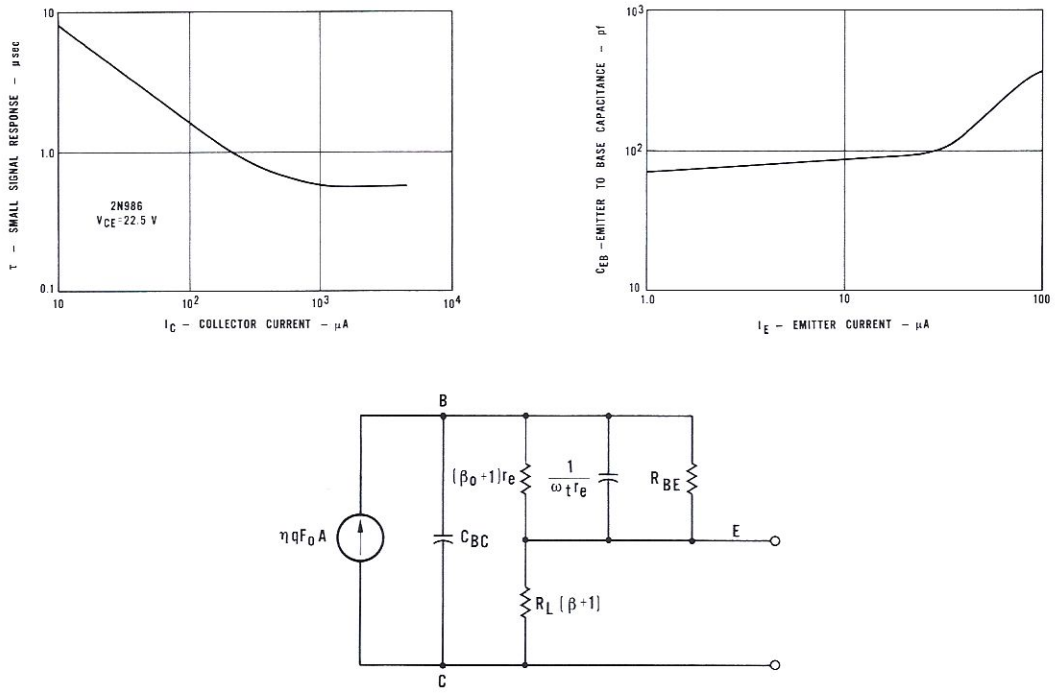

FIG. 3. Equivalent circuit and time dependence of current of phototransistor.

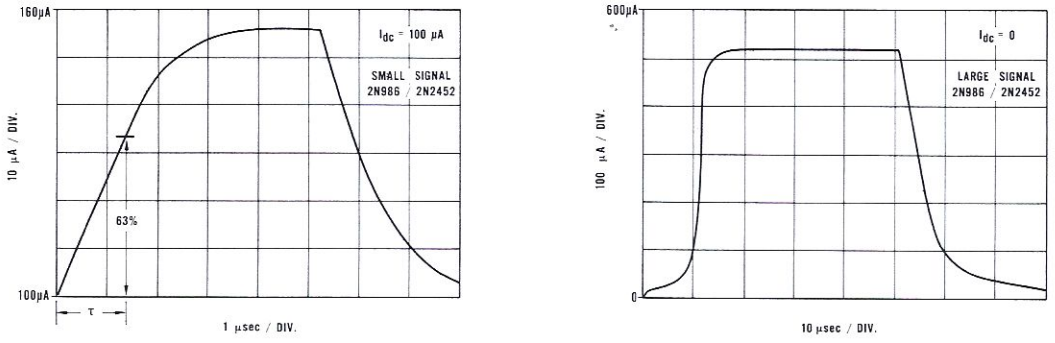

FIG. 4. Current waveforms resulting from pulsed light.

APPENDIX

Steady-State Phototransistor Action

Assuming that the base and the collector-base depletion layer are the only illuminated areas, we obtain a collector-base diode current density $J_{cb\ell}$.

The remaining holes charge the base so that the emitter injects minority carriers into the base. (The emitted current density is J_e.)

A fraction of the emitter minority-carrier current αJ_e reaches the collector and the remainder, $(1 - \alpha)J_e$, recombines with the majority-carrier charge in the base region. The fraction of the emitted current which recombines in the base is equal to the majority-carrier photocurrent

$$J_{cb\ell} = (1 - \alpha)J_e$$

The total current density at the collector is

$$J_{c\ell} = \alpha J_e + (1 - \alpha)J_e = J_e$$

so that the current continuity equation is satisfied, and the ratio of total collector current to photoelectric current is

$$\frac{J_{c\ell}}{J_{cb\ell}} = \frac{\alpha J_e}{(1 - \alpha)J_e} + \frac{J_{cb\ell}}{J_{cb\ell}} = \beta + 1$$

Thus for a device with active area A

$$I_{c\ell} = (\beta + 1)\, I_{cb\ell} = (\beta + 1)\eta q F_o A$$

if there is no dark current. In the general case, the dark current (I_{CEO}) is not negligible, so it is added to the result above, obtaining

$$I_c = (\beta + 1)\eta q F_o A + I_{CEO}$$

Note that the dark current can be written by the familiar relation

$$I_{CEO} = I_{CO}(\beta + 1)$$

This shows the similarity of light current and thermally generated dark current. The steady-state current can then be written

$$I_c = (\beta + 1)(\eta q F_o A + I_{CO})$$

With this current flowing through the current-sensing external (load) resistor R_L, then

$$e_{out} = I_c R_L = (\beta + 1)(\eta q F_o A + I_{CO})R_L$$

which is equivalent to the steady-state result derived from the model in Fig. 3.

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